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13 January 1995

Dr. Ed Ruitberg
HST Operations and Ground Systems Project Field Office
ST Science Institute
3700 San Martin Drive
Baltimore, MD 21218

Dear Ed:

This letter is my technical report of activities on my grant NAG5-1620. This report covers my work for the time interval 1 July to 31 Dec 1994.

During this time I made many trips to Baltimore to work with Bill Fastie and David Golimowski on the joint Fastie/Schroeder GTO program. We are getting lots of good data and have started to look carefully at it. So far there is nothing exciting to report, but we certainly are learning a great deal about scattered light levels in PC2.

The nature of this report is primarily a set of attachments, four in all. Let me comment briefly on each of them. During the late summer, after our first detailed analysis of images taken last March, David and I made some calculations of model images, both perfect and with the HST optical aberrations added. David used TINY TIM and I used my software. The aim was to calculate the average counts per pixel through different filters for a given incident total flux. Some of the results of this work are found in Attachment A. With that as input, I then analyzed some of the results on scattered light obtained by John Krist. This work is summarized in an attached internal report labeled B.

The scattered light level from our initial images was greater than expected and we decided to take our next set of images with the star off the edge of the chip in hopes of dramatically reducing this background light level. Unfortunately, the scattered light level was not changed by a large factor and we opted to take all remaining pictures with the star again centered in the PC2 chip. A discussion of this is found in Attachment C, an internal report written by Bill Fastie.

The last attachment, D, is simply a listing of various IDL programs which I wrote for the purpose of seeing how easy or difficult it is to extract faint images from the background around a bright star. With these programs I can take a perfect model image, add statistical photon noise to each pixel, and convolve the image with an MTF degradation factor. When a planet signal is added to such an image (pmod201.pro), or many such images, it is then possible to look for pixels whose signal is some number of sigmas above the local background. This work is still in progress and I expect we will know soon the level to which we can "dig out" weak signals.

(NASA-CR-197388) SUPPORT OF GTO OBSERVATIONS ON HST Technical Report, 1 Jul. - 31 Dec. 1994 (Beloit Coll.) 26 p

N95-70744

Unclas

Z9/89 0041097

In the meantime, my sabbatical leave continues, as do my frequent trips to Baltimore. Observations of Tau Ceti are in hand and several other stars will be observed soon. We still believe that all of the lab and computer work done these past several years will finally pay off, and we look forward to some very exciting scientific results.

Sincerely yours,

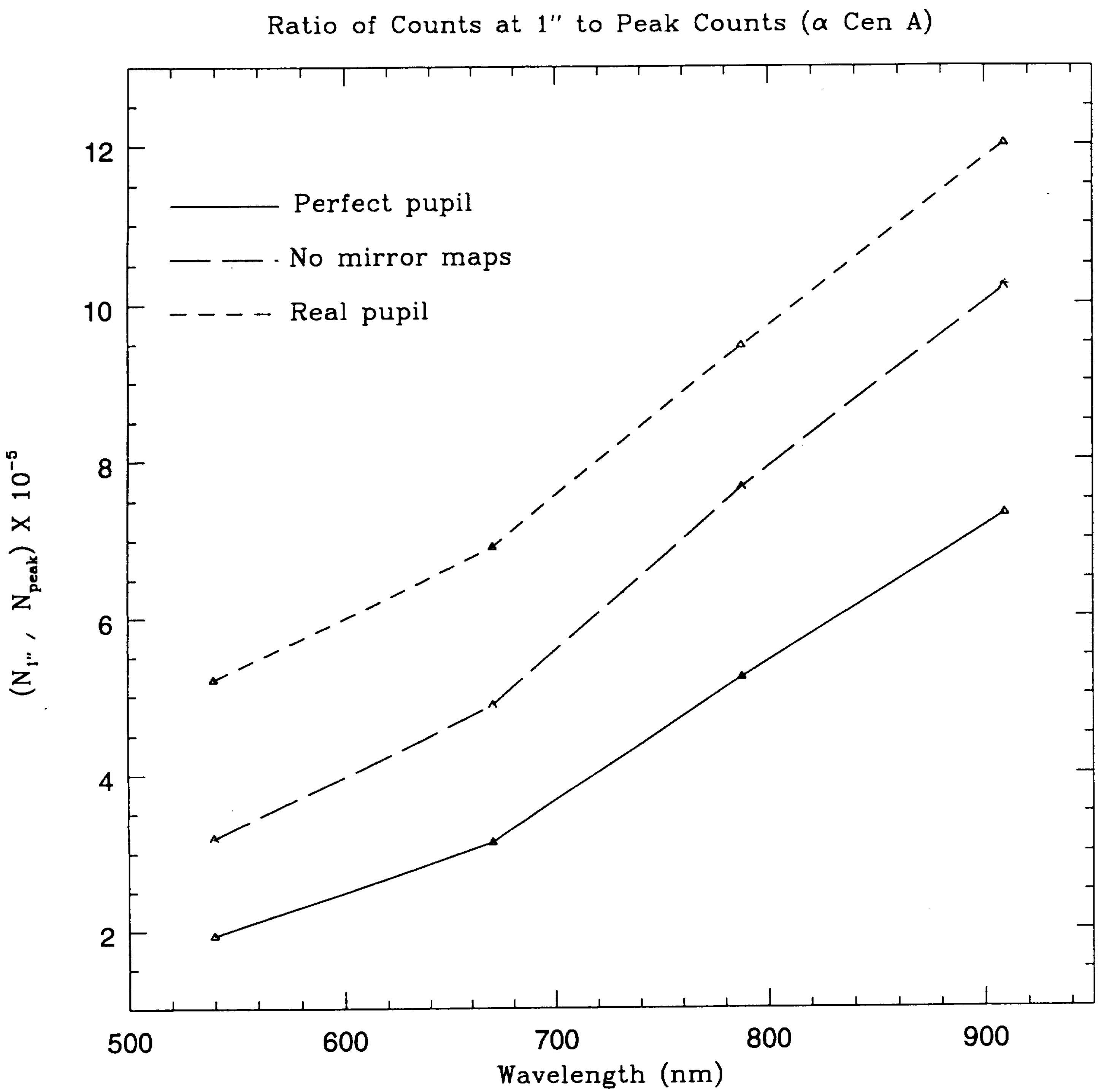
Dan Schroeder

Daniel J. Schroeder
7th team GTO

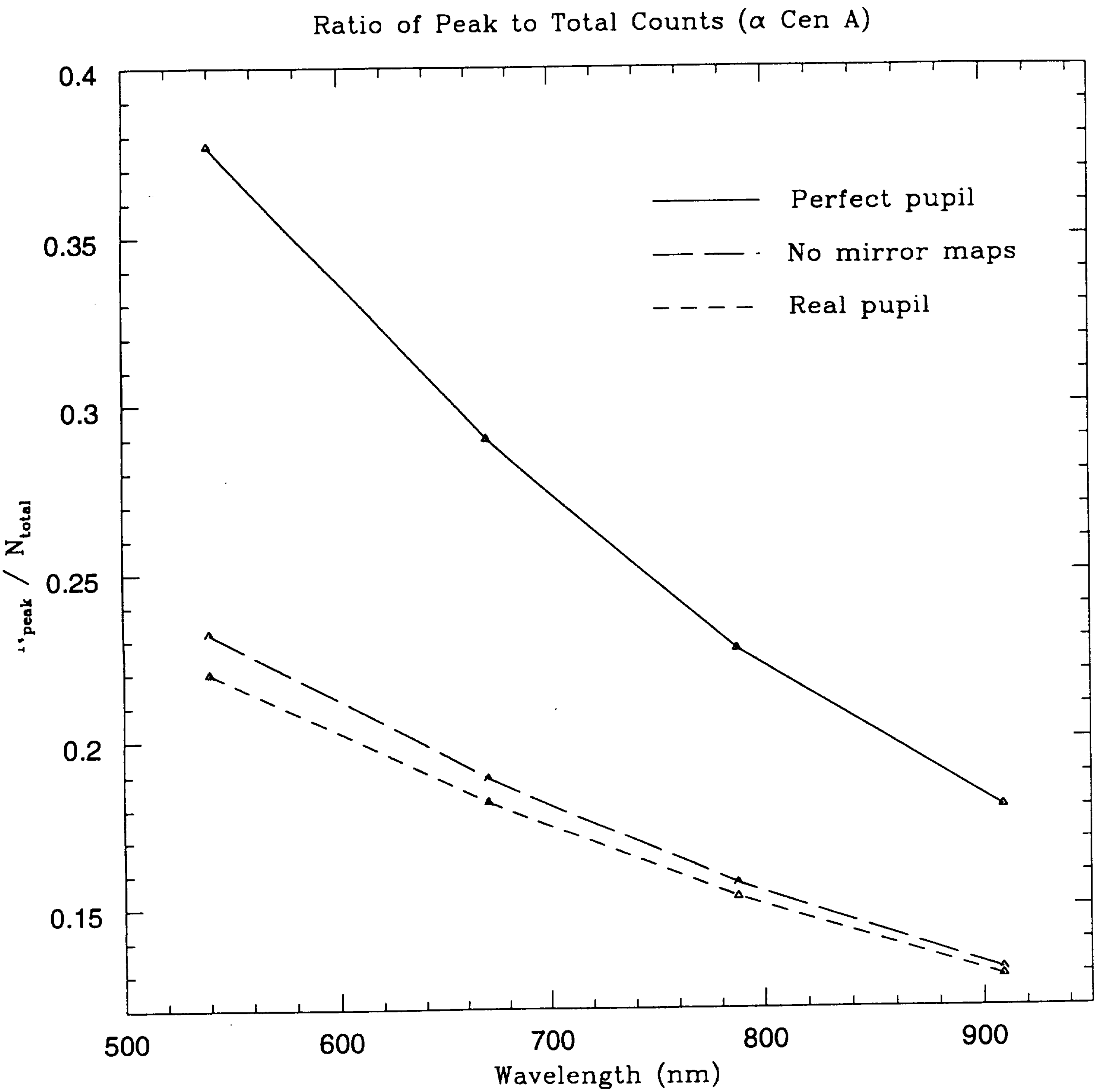
copies: NASA Center for Aerospace Information
(2 including enclosures)

Gloria Blanchard
Grants Officer
(letter only)

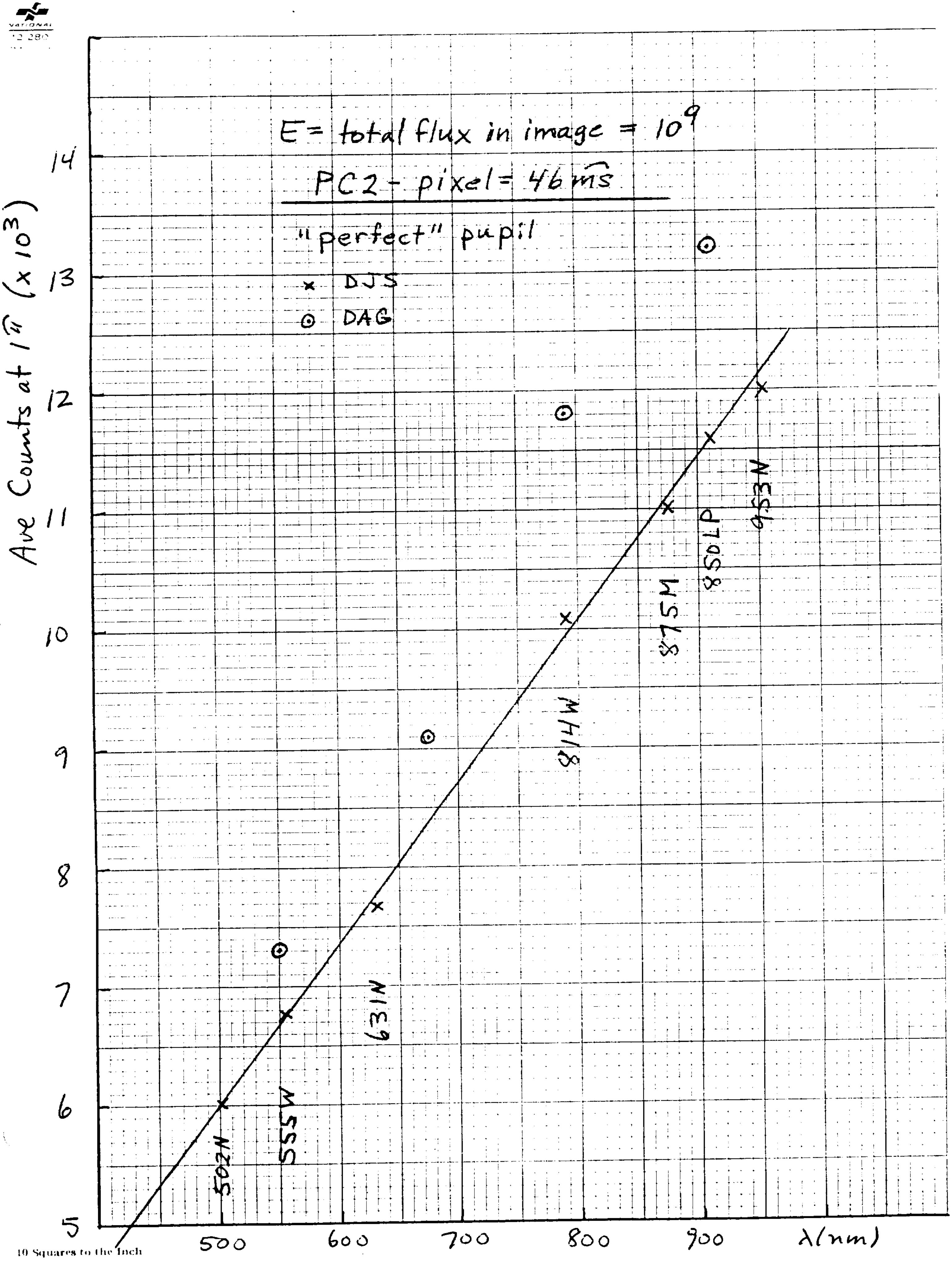
A

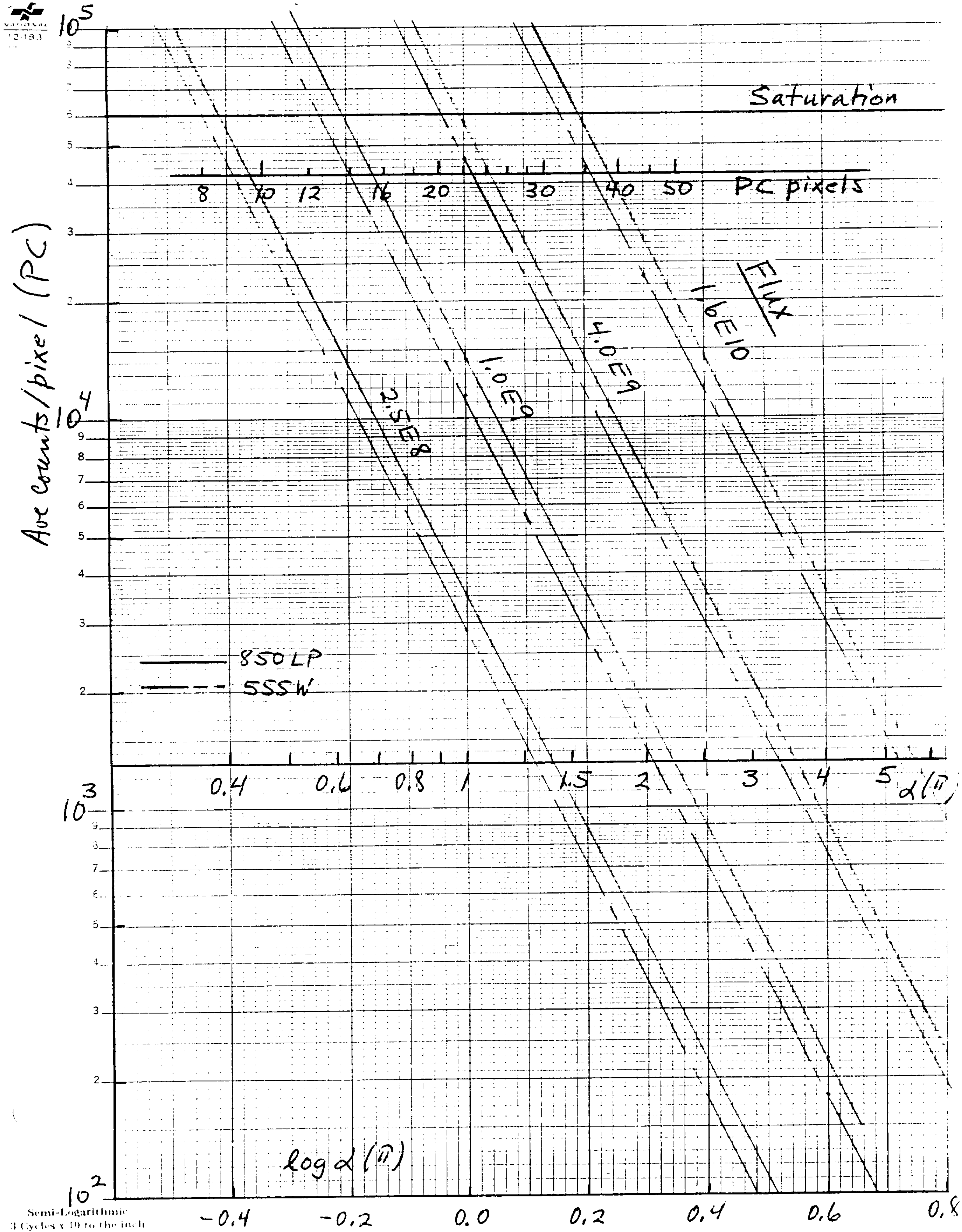


Ratio of Counts at 1" to Peak Counts (α Cen A)
Perfect pupil
No mirror maps
Real pupil
2
4
6
8
10
12
($N_{1''}$ / N_{peak}) X 10^{-5}
500
600
700
800
900
Wavelength (nm)



Ratio of Peak to Total Counts (α Cen A)
Perfect pupil
No mirror maps
Real pupil
0.4
0.35
0.3
0.25
0.2
0.15
500
600
700
800
900
Wavelength (nm)


E = total flux in image = 10^9
PC2 - pixel = 46 mas
"perfect" pupil
× DJS
⊙ DAG
Ave Counts at 1" (x 10^3)
λ(nm)
502N
555W
631N
814W
875M
850LP
953N
5
6
7
8
9
10
11
12
13
14
500
600
700
800
900
10 Squares to the Inch



Saturation
PC pixels
8
10
12
16
20
30
40
50
Flux
1.6E10
4.0E9
1.0E9
2.5E8
850LP
555W
0.4
0.6
0.8
1
1.5
2
3
4
5
α (")
log α (")
-0.4
-0.2
0.0
0.2
0.4
0.6
0.8
Ave counts/pixel/(PC)
10^5
10^4
10^3
10^2
Semi-Logarithmic
3 Cycles x 10 to the inch

B

REVISED

8 September 1994

To: Bill Fastie, David Golimowski
Chris Burrows, John Krist

From: Dan Schroeder

Subj: Scattered light

[[I learned from John yesterday afternoon that my assumption about the filters used for the overexposed images he analyzed was not correct. It turns out that my error has little effect on my analysis; following is the revised text in which my error about filters is corrected.]]

Accompanying this prose is a set of graphs which I constructed in an attempt to get an idea of the scattered light level in WFPC2. My analysis is based on model calculations by me on perfect images, David on Tiny Tim models (both perfect and with all aberrations added), and John's measures on both WFC and PC images of Delta Cas through a 502N filter. My goal was to compare model results with real data and to see, at the least, if the results were consistent.

Let me proceed by first describing the approach. I used a program which gives PSF maps for the PC pupil for any specified filter. There are no aberrations in this approach and thus the PSF can be calculated in an analytic form. These results were compared with some done by David using Tiny Tim with no aberrations and no mirror maps. Our results for the average intensity at one arcsec agreed to better than 10% over a range of filter choices. David also did the same calculations for the PC pupil with aberrations and mirror maps added. A comparison of the average intensities at one arcsec gives what I call a "fudge-factor" - the factor by which my results for a perfect pupil must be adjusted to take into account OTA and camera defects. This factor is about 1.7 at 555W and 1.4 at 814W. (I extrapolated these results to get 1.8 at 502N.)

Using these results I made the graph in Fig. 1 - the average count per PC pixel for four different incident flux levels. This graph assumes an r^3 falloff with field angle, hence no scattered light from any source.

Figure 2 shows data on overexposed Delta Cas images. Using a calibrated pencil and eyeball, I measured the flux/device pixel at selected angles for the PC data. These values were then plotted on a log-log scale in Fig. 3 - shown as x's. Because Fig. 2 is based on total flux = 1, I could take the 1E9 line from Fig. 1 and transfer it to Fig. 3. (The 502N line is close to that of 555W. Change 631 to 502 on Fig. 3.) The corresponding results for the WFC data are in Figs. 4-6. (Change 410M to 502N on Fig. 6.) The final graph shows the difference between numbers from John's graph and the calculated models with no scattered light.

Now for some comments:

1) Figures 1 and 4 show the angles at which the average count/pixel reaches saturation. For a flux level of about 8E8, approximately that for the Delta Cas exposures, non-saturation should start in at about 13 PC pixels and 9 WFC pixels from the core. But the data for the real images shows saturation to about 18 pixels for both cameras. This suggests that bleeding is not confined to columns.

2) Shortward of 3 arcsec, the slope of a line through the data points on Figs. 3 and 6 is greater than -3. This is especially noticeable for the WFC data in Fig. 6. This suggests that the saturated core may be affecting the unsaturated region to about 3 arcsec. I cannot think of any other reason for a slope steeper than -3.

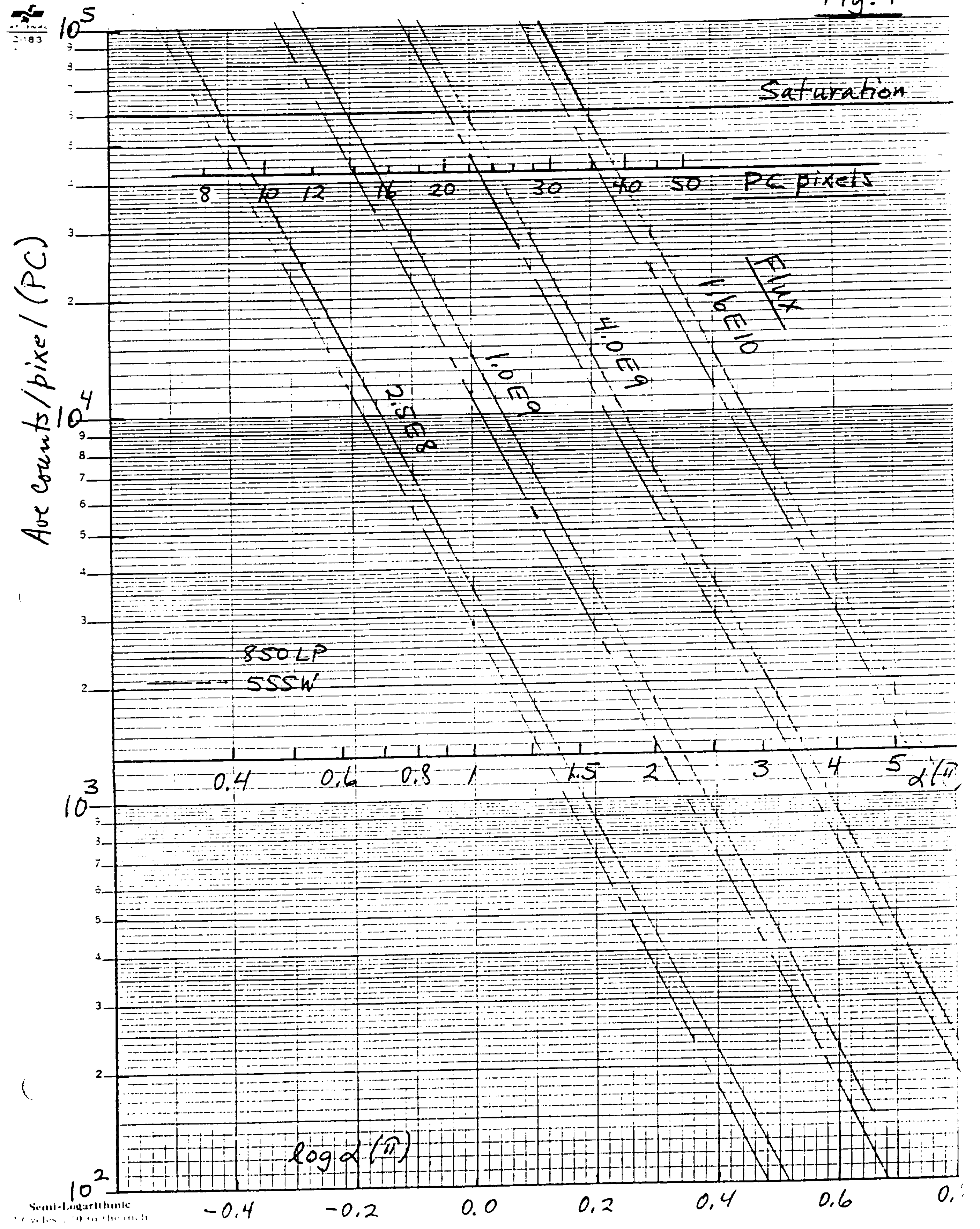
3) Longward of 3 srcsec the slope of the data points is about -2. The difference data in Fig. 7 shows a slope of about -1.5 in the far wings of the PSF as well as a very pronounced change in slope at angles less than 3 arcsec.

4) If the difference data is correct, then we may have a measure of the scattered light level from 3-10 arcsec. It may be worth taking this analysis to larger angles, say the edge of the chip, and assume that all of the scattered light is included. An integration over the chip (less the saturated core area) would give a number for comparison with the incident flux. (Chris or John, how about doing this since you have the actual data?)

I am sending this material to you for comments and reactions. Have I neglected some important factor which makes this analysis invalid? Or does it give us some insight into the level of scattered light to expect when a star is overexposed by a few orders of magnitude.

I await your comments. Starting Friday, 9 Sept, and for all of the following week, I can be reached at 715/277-2033 or by e-mail at schroeder@beloit.edu. Cheers.

Fig. 1


Saturation
PC pixels
8
10
12
16
20
30
40
50
Flux
1.6E10
4.0E9
1.0E9
2.5E8
Ave counts/pixel/(PC)
850LP
555W
0.4
0.6
0.8
1
1.5
2
3
4
5
α('')
log α('')
-0.4
-0.2
0.0
0.2
0.4
0.6
Semi-Logarithmic

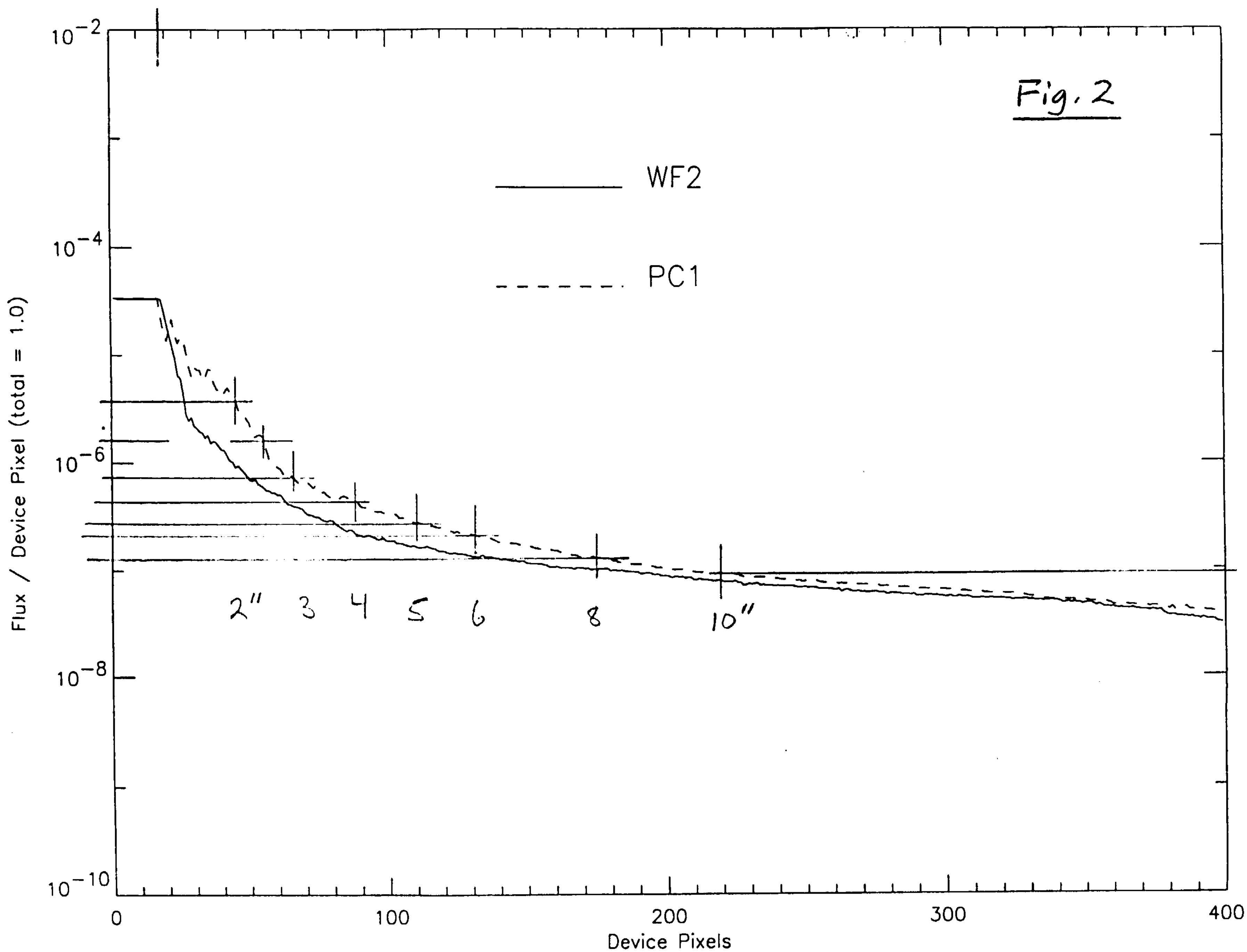

WF2
PC1
2"
3
4
5
6
8
10"
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
Flux / Device Pixel (total = 1.0)
0
100
200
300
400
Device Pixels

Fig. 2

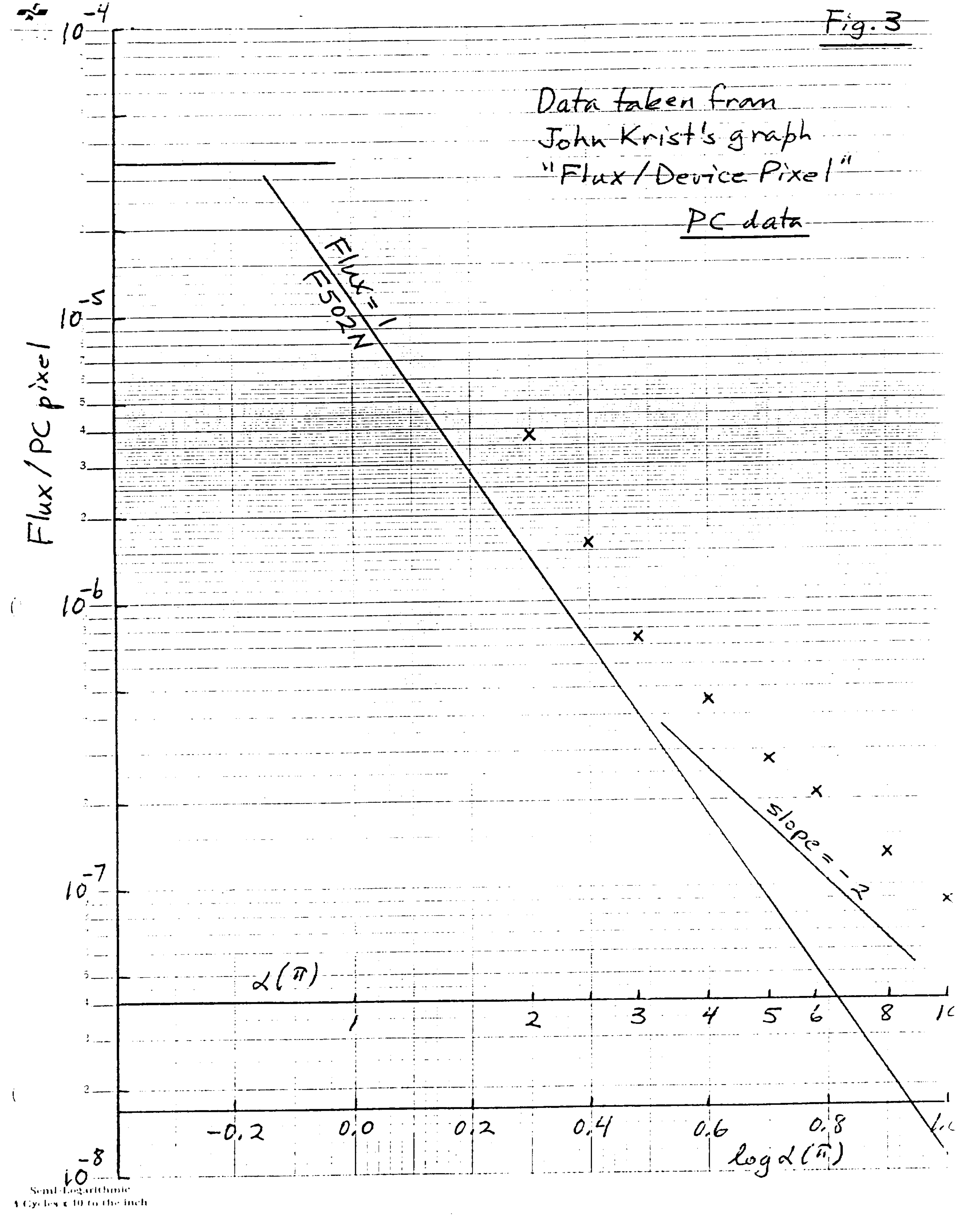


Fig. 3
Data taken fron
John Krist's graph
"Flux/Device Pixel"
PC data
Flux = 1
F502N
slope = -2
Flux / PC pixel
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
$\alpha(\pi)$
1
2
3
4
5
6
8
10
-0.2
0.0
0.2
0.4
0.6
0.8
1.0
$\log\alpha(\pi)$
Semi-Logarithmic
4 Cycles x 10 to the inch

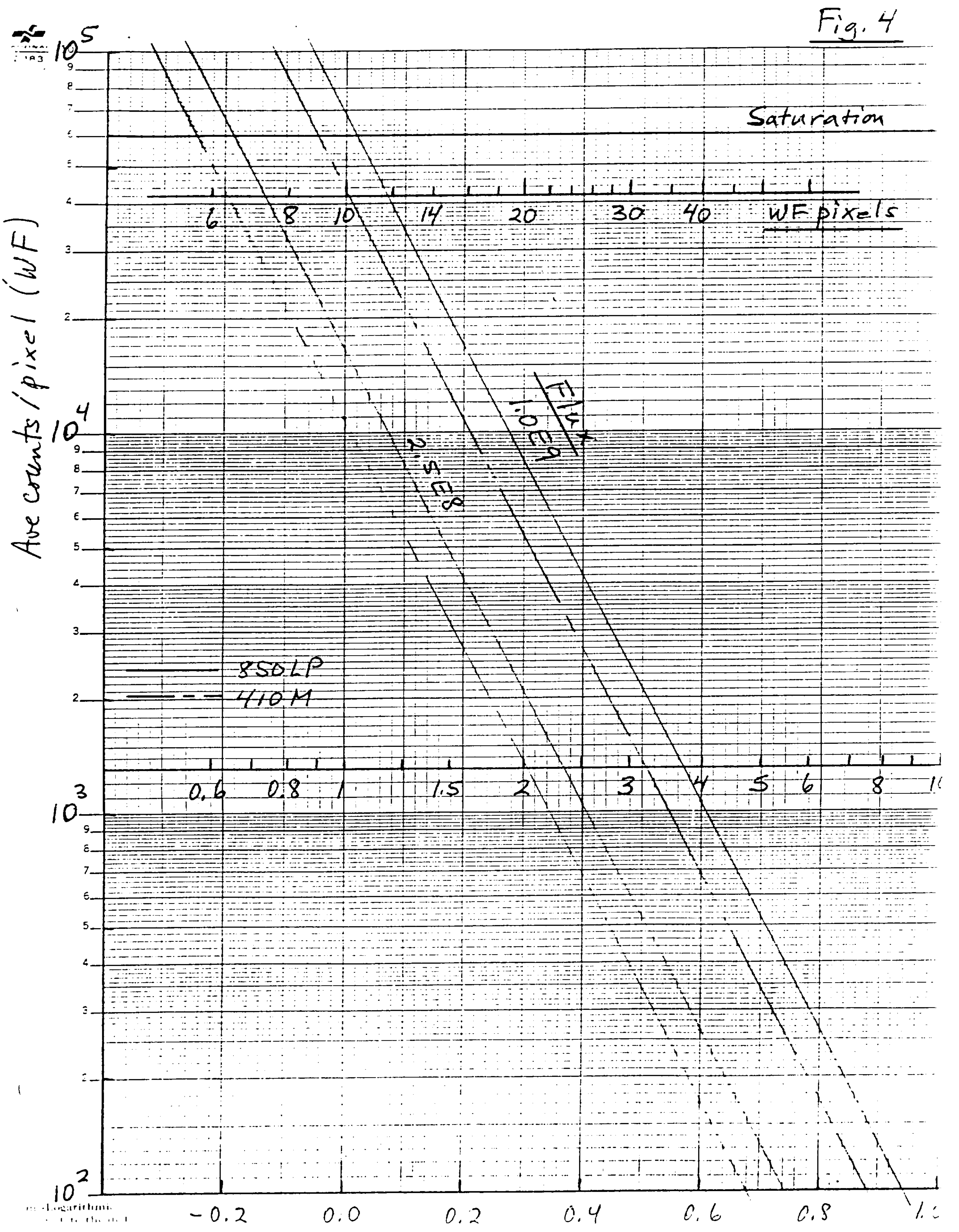


Fig. 4
Saturation
WF pixels
6
8
10
14
20
30
40
Ave counts / pixel (WF)
10^5
10^4
10^3
10^2
F/4
1.0E9
2.5E8
850LP
410M
0.6
0.8
1
1.5
2
3
4
5
6
8
-0.2
0.0
0.2
0.4
0.6
0.8

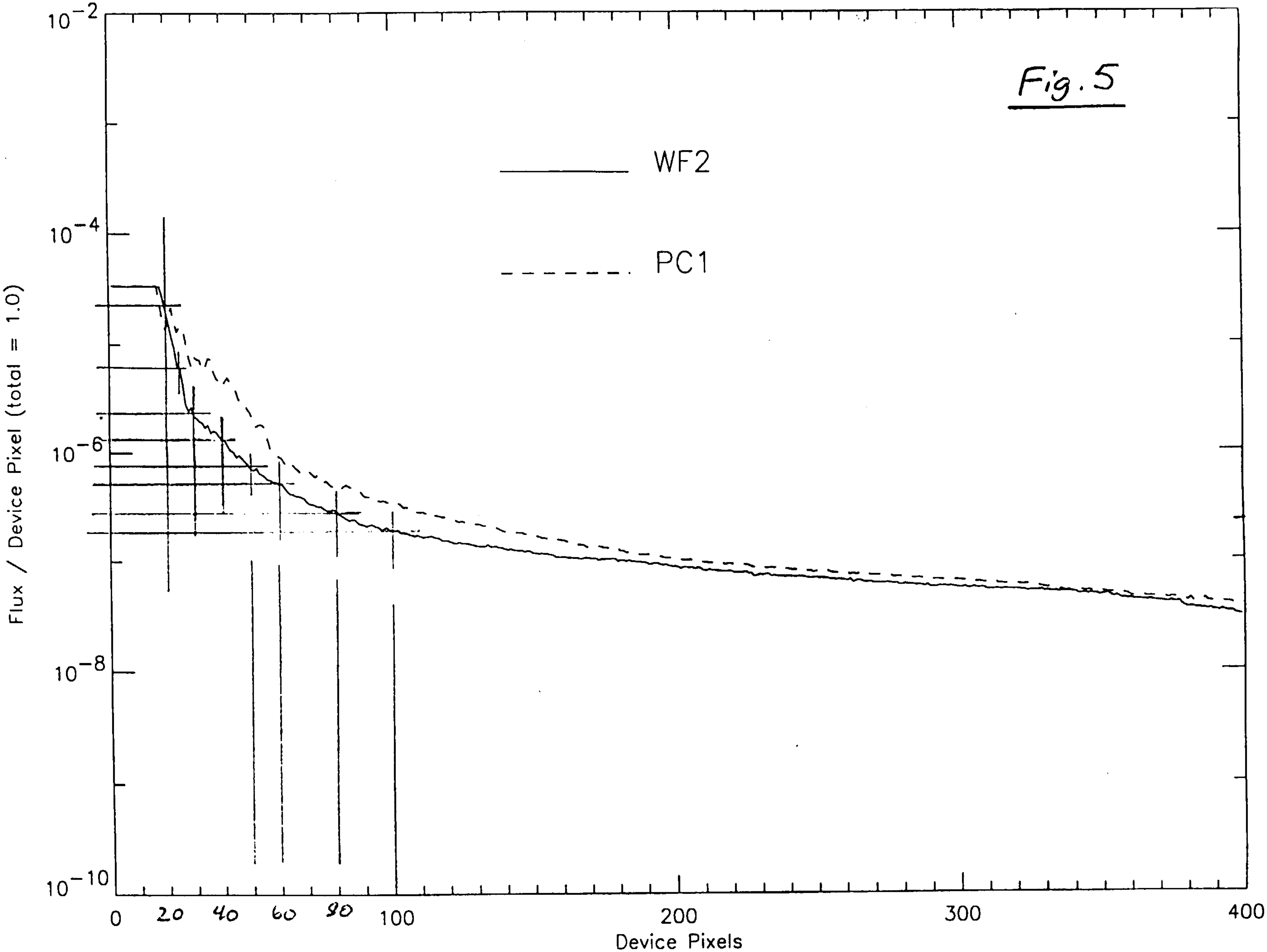
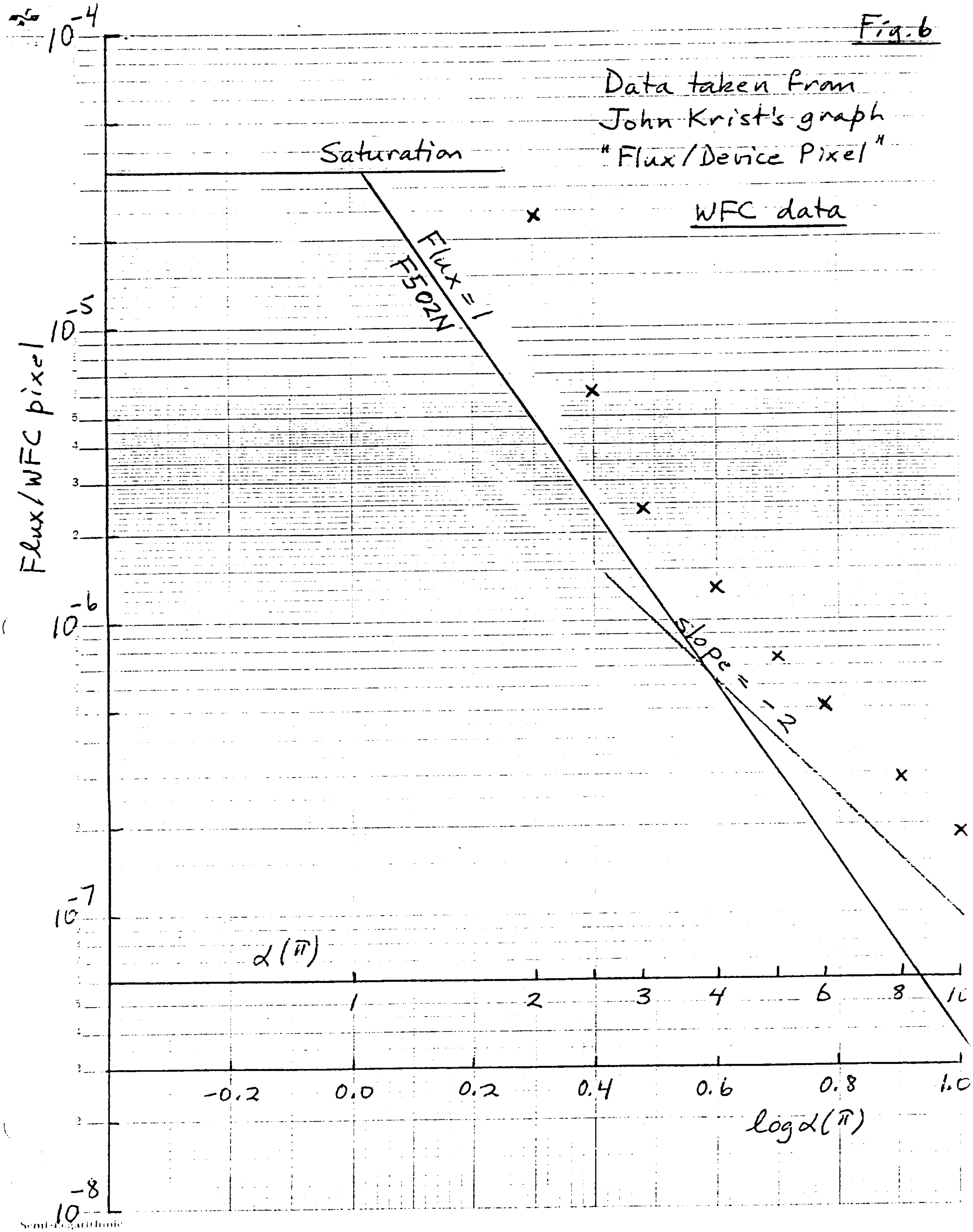

WF2
PC1
Flux / Device Pixel (total = 1.0)
Device Pixels
10^-2
10^-4
10^-6
10^-8
10^-10
0
20
40
60
80
100
200
300
400

Fig. 5



Semi-Logarithmic
4 Cycles x 10 to the inch

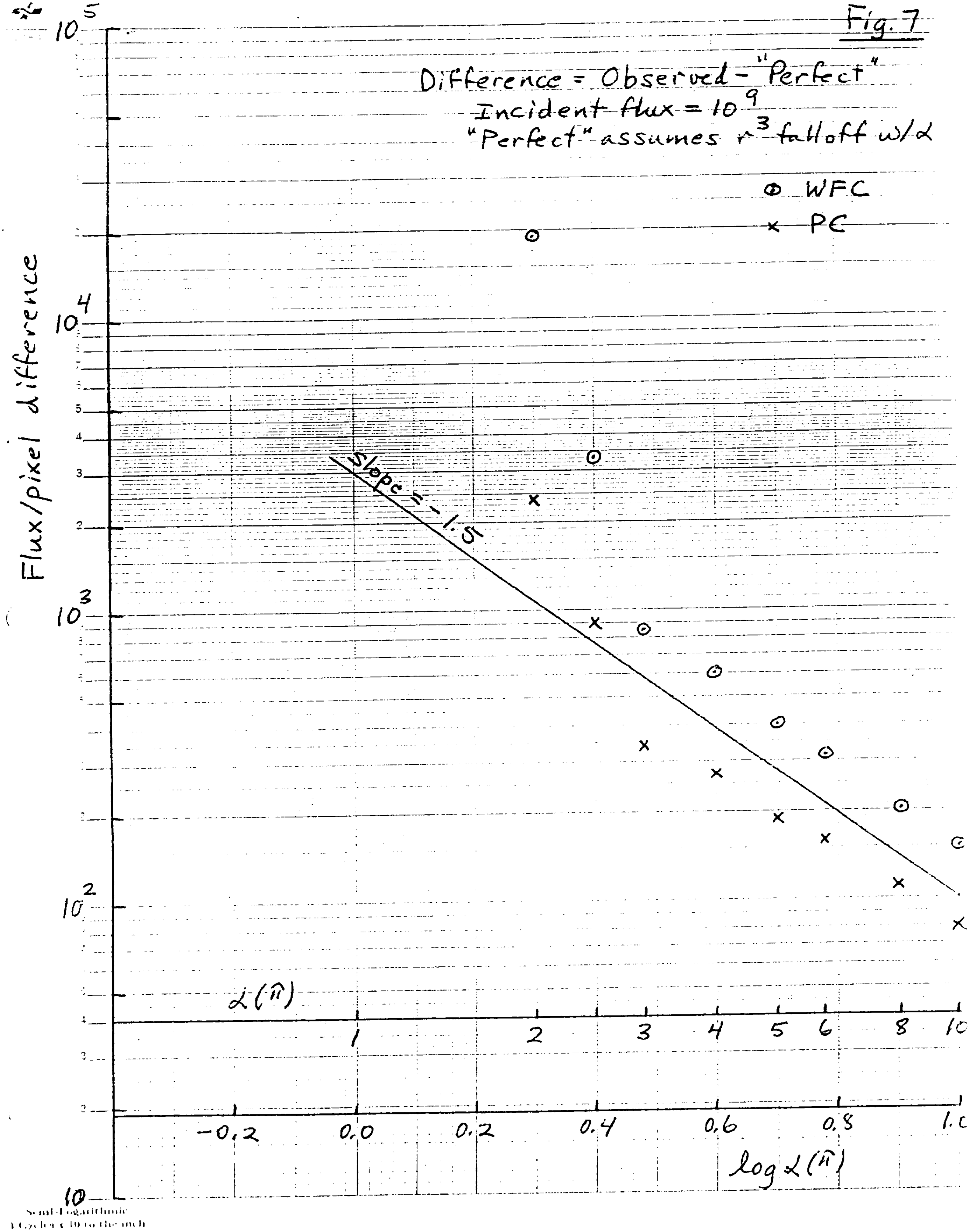


Fig. 7
Difference = Observed - "Perfect"
Incident flux = 10^9
"Perfect" assumes r^-3 falloff w/α
WFC
PC
Slope = -1.5
Flux/pixel difference
α (")
log α (")
10^5
10^4
10^3
10^2
10
1 2 3 4 5 6 8 10
-0.2 0.0 0.2 0.4 0.6 0.8 1.0
Semi-Logarithmic
1 Cycle x 10 to the inch

WIDE FIELD/PLANETARY CAMERA OBSERVATIONS

WM. G FASTIE

C

The initial approach of our Extra Solar Planet Search Program on HST was to use narrow band filters to produce resolved Airy diffraction rings of a star over a 12 arcsec diameter and to search for planets on the faintest Airy fringes which were as much as 25 times fainter than the neighboring fringes. This technique promised us a very small percentage of the total search field, but good statistics.

On March 11, 1994, we observed Epsilon Eri with filters 631N and 953N. The Airy diffraction rings were resolved over a 20 arcsec diameter circle with both filters in the planetary camera CCD but the maximum observed fringe contrast was 4 to 1. The poor contrast was the result of a defect in the Loral CCD detector. It was obvious that our planet search using the original technique would be futile.

We therefore changed gears for our second set of observations and switched to wide band filters which would further smooth the Airy ring pattern but still provide an r^{-3} intensity profile if there was no scattered light from the telescope or camera. Also, within the search field, perhaps 100 times as much area was available as compared with the original technique. We also placed the star image one arcsec beyond the plus edge of the Planetary Camera, i.e. 22 px outside the 800th pixel in the x direction and at the 267th px in the y direction.

The edge of the Loral CCD is in the plane of the CCD pixels, is flat and specularly reflecting. The CCD is tilted at an angle of 1.5 degrees so that a stellar image at the center of the chip is reflected through the hole in the primary mirror of the camera, misses the secondary mirror and is lost, thus ghost images are avoided. We used wide band filters 622W and 850LP, and observed Epsilon Eri again on September 11, 1994.

Our analysis of these new data to date has been limited to evaluating the detector performance. We have observed that the Airy pattern radially decays with a power law of $r^{-2.4}$ as far as 30 arcsec from the star (Fig. 1). Analysis of the March 1994 data shows that if we place the star at the center of the PC field, and use many short exposures to provide the necessary photon flux, we can also achieve an $r^{-2.4}$ power law for the Airy background pattern plus scattered light. Because the off detector mode allows us to observe less than half of the star field, we have decided to place our target stars at the center of the PC chip. This approach is much more efficient in preserving our precious observing time.

Our target stars during the next few months include Tau Ceti, Procyon, HD16160, and Alpha Cen A and B. We also plan follow-on observations of each of these stars with the shortest practical time gaps between the first and second observations. This will permit us to use the same guide stars and the same roll angle for the first and second observation. This technique may make it possible to subtract the first and second visit data without flat fielding, thus avoiding flat fielding errors and anomalies in the diffraction patterns such as ghosts and "holes" and to cancel scattering streamers that appear in the images. In addition, the large number of images we take with each filter (possibly as many as 50) allows us to sort out those few images which may be subjected to larger than normal pointing errors and to correct (at least in part) for generic pointing errors between the first and second visit.

The data shown in Fig. 1 is for an exposure with approximately 4.0E9 detected photoelectrons. We get the same detected flux for a V=0 star, such as Alpha Cen, with an F555W filter and exposure time of 0.7 sec or an F547M filter with exposure of 1.6 sec. A plot of this star signal beyond one arcsec is shown in Fig. 2. Also shown there is a line for the rms noise of the star signal; this line also represents the noise for any faint stellar companion whose signal is small compared to the Airy background. The stellar magnitude scale for a companion is shown on the right side of Fig. 2.

If Alpha Cen had a Jupiter just like our sun's Jupiter, it would be 4 arcsec from Alpha Cen, as seen from the Earth, and be approximately V=21. This companion would not be detectable in a single exposure at the flux level in Fig. 2. If, however, 50 such pictures were added, then the relevant data is as shown in Fig. 3. Included in Fig. 3 are lines from which the magnitude of a companion required to obtain S/N=3 or S/N=10 as a function of distance from Alpha Cen can be found.

We have only recently installed a flight qualified Loral Detector in our HST simulator, which has diffraction limited optics and illuminates a WF/PC 1 camera provided by JPL which also has diffraction limited optics. We will obtain laboratory data with the Simulator to compare with the flight data to confirm and support our flight data.

Fig. 1

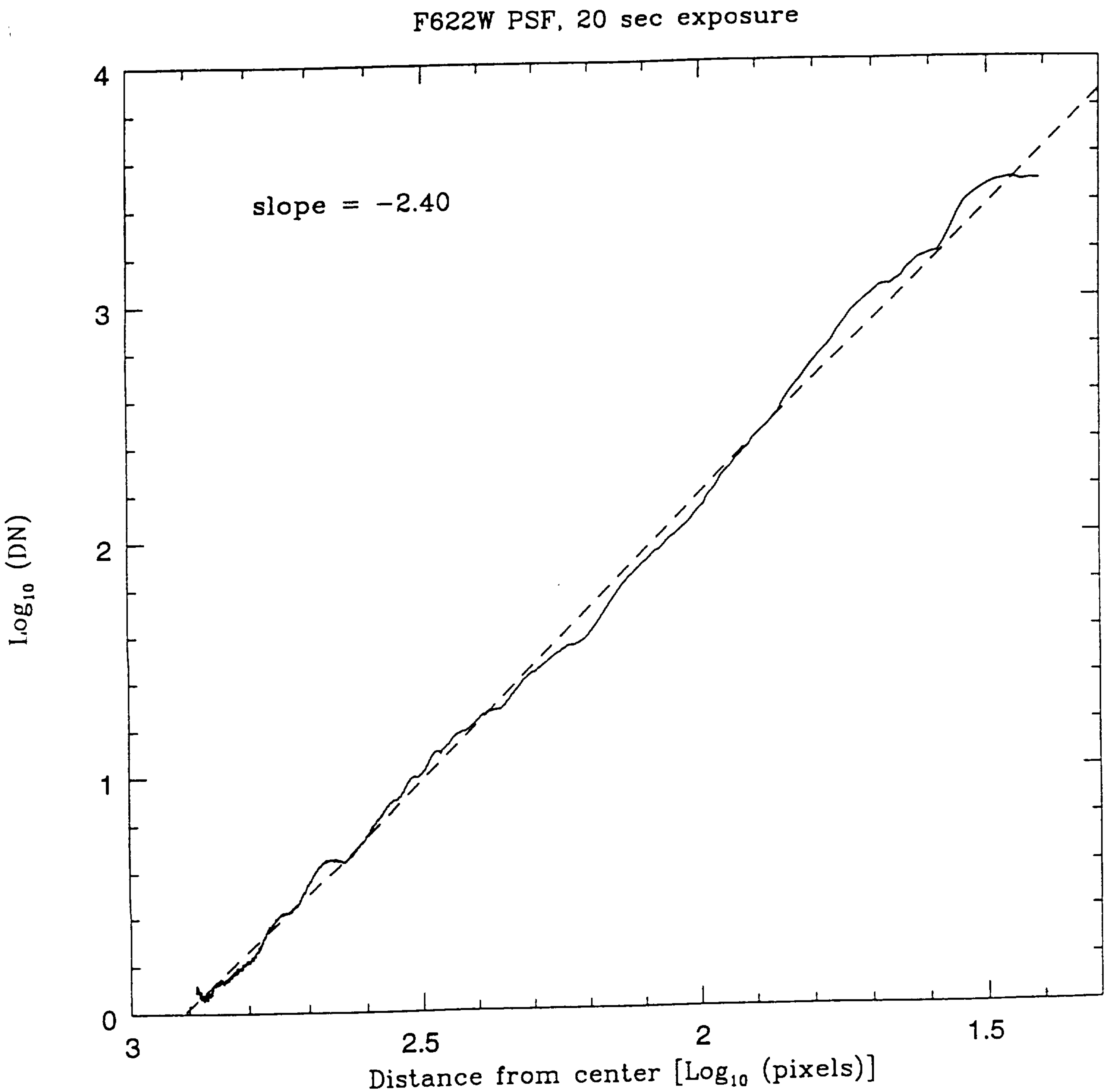


Figure 1. Plot of point-spread function of Epsilon Eridani through F622W filter. The star is positioned at PC coordinates (822, 267). The solid curve is an azimuthally averaged horizontal cut through the median filtered image. The dashed line is the best-fit power law to the data, r^(-2.4).

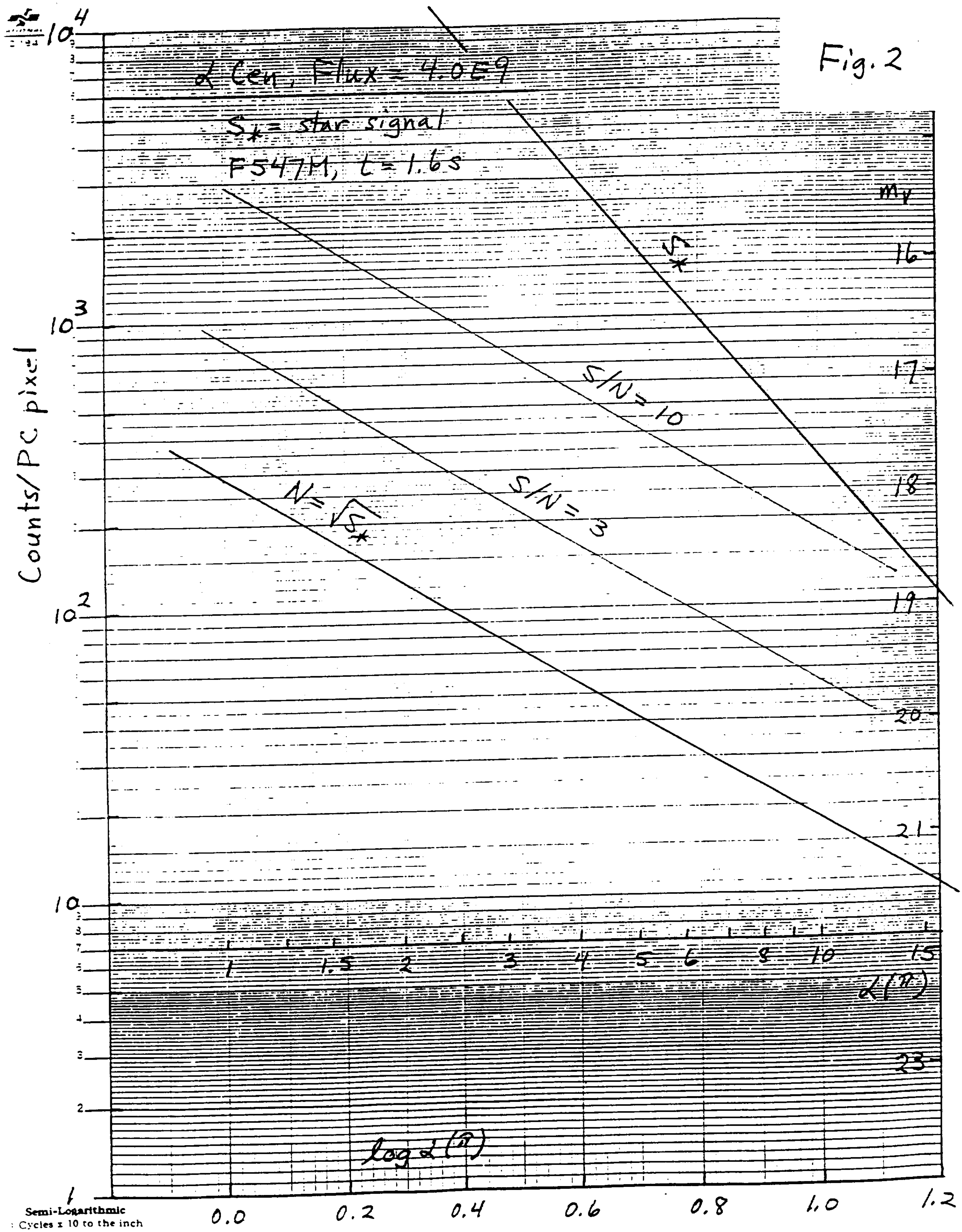
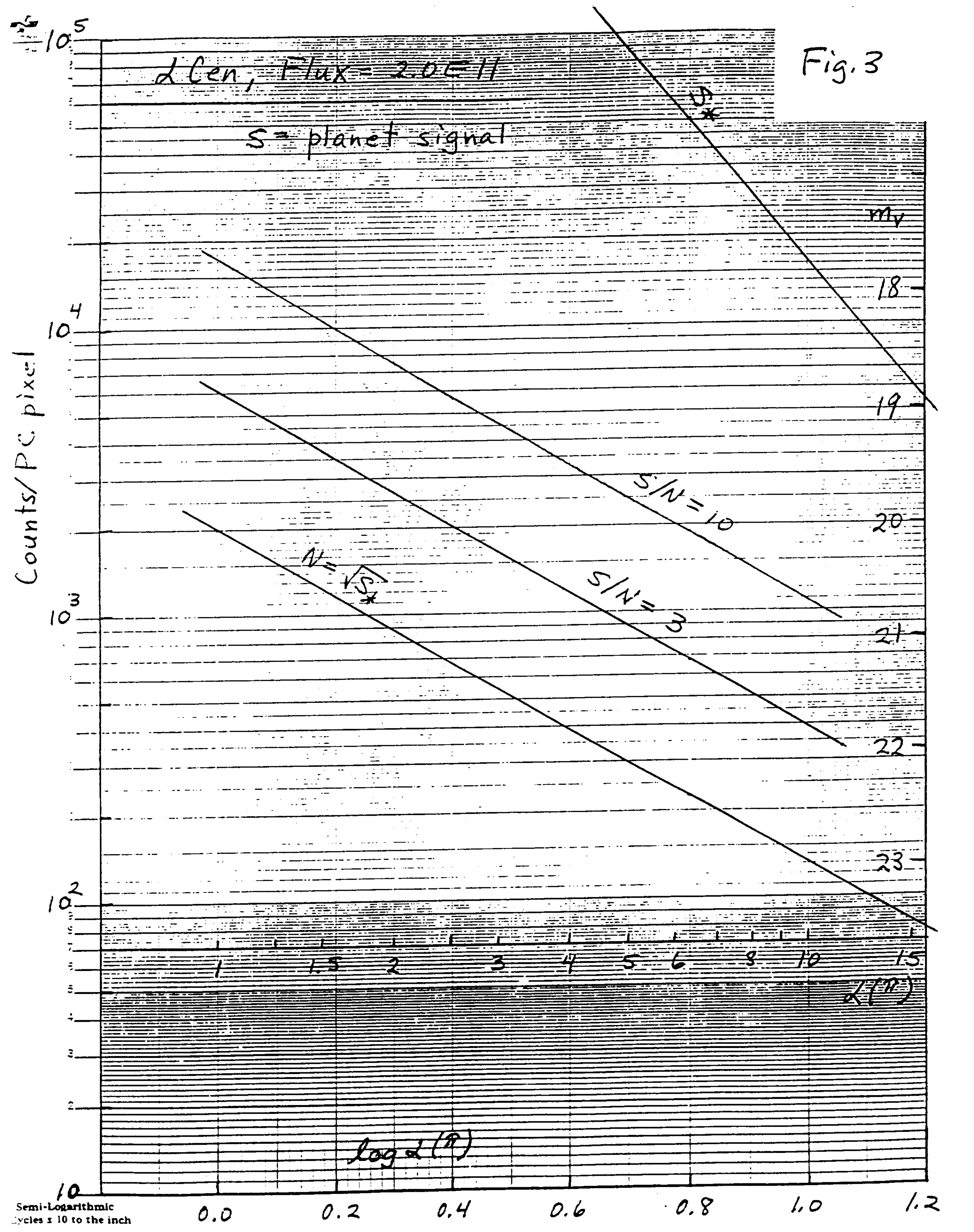


Fig. 2
α Cen, Flux = 4.0E9
S_* = star signal
F547M, t = 1.6s
S_*
S/N = 10
S/N = 3
$N = \sqrt{S_*}$
Counts/PC pixel
10^4
10^3
10^2
10
1
m_V
16
17
18
19
20
21
23
1
1.5
2
3
4
5
6
8
10
15
α (")
log α (")
0.0
0.2
0.4
0.6
0.8
1.0
1.2
Semi-Logarithmic
Cycles x 10 to the inch



α Cen, Flux = 2.0E11
S = planet signal
Fig. 3
S_*
m_V
18
19
20
21
22
23
S/N = 10
S/N = 3
$N = \sqrt{S_*}$
Counts/PC pixel
10^5
10^4
10^3
10^2
10
1
1.5
2
3
4
5
6
8
10
15
α(")
log α(")
0.0
0.2
0.4
0.6
0.8
1.0
1.2
Semi-Logarithmic
Cycles x 10 to the inch

APPENDIX A

Signal-to-Noise Considerations in the Detection of Faint Stellar Companions

A perfect detector has a signal-to-noise ratio (S/N) given by

$$S/N = \frac{S}{\sqrt{S+B}}, \qquad (1)$$

where S is the desired signal and B is the unwanted background signal. For the case where we want to see a faint companion in the presence of its parent star, S is the signal of the companion and B is the signal from the Airy background and scattered light. If the companion is a planet, then over any reasonable distance from the parent star we have B>>S and, to a good approximation,

$$S/N = \frac{S}{\sqrt{B}}. \qquad (2)$$

Assume that the star has peak intensity L when imaged by HST. Based on measures like those in Fig. 1 we can write

$$B = KL/r^{2.4} \qquad (3)$$

where K = constant, and r is the angular distance from the stellar image.

Combining Eqs. (2) and (3) gives

$$S = \sqrt{KL}\,(S/N)/r^{1.2} \qquad (4)$$

For a given S/N we see that S gets larger as r gets smaller. <u>The closer to the star, the brighter the planet must be in order to be discovered.</u>

The fact that a planet of a particular radius and albedo varies in brightness S as 1/r^2 does not alter the conclusion deduced fromEq. (4). It is true, however, that a particular planet will be more easily detected closer to a star because it gets brighter faster than the background noise. This can be seen by substituting S = $K'L_p/r^2$ into Eq. (4) and solving for L_p. The result is

$$L_p = \frac{\sqrt{KL}}{K'}(S/N)\,r^{0.8} \qquad (5)$$

Note that L <u>decreases</u> as r decreases.

Dan Schroeder
Alan Uomoto

4 November 1994

```
;pns101.pro (pseudo-image + noise)                                          D
;test program using "randomn" to simulate adding noise to images
;pseudo-image used as starting point has same count on each pixel
;planet count is added to single pixel


im=fltarr(101,101)
read,'  star count = ',count
read,'  planet count = ',pcount
im=im+count                                 ;each pixel given same count
npix=float(n_elements(im))
imsum=fltarr(101,101)
iplan=fltarr(101,101)
iplan(40,40)=pcount                         ;single pixel given pcount
;
;noise arrays calculated
starn=sqrt(im)
plann=sqrt(iplan)
;
read,'  number of images =  ',m
  for i=0,m-1 do begin
    nfs=randomn(seed,101,101)
    snoise=starn*nfs                             ;star signal noise
    nfp=randomn(seed,101,101)
    pnoise=plann*nfp                             ;planet signal noise
    imn=im+snoise+iplan+pnoise
    imsum=imsum+imn
  endfor
    print,'   '
    avc=total(imsum)/npix                        ;average count, sum
    m2c=total(imsum^2)/(npix-1.)                 ;mean square count, sum
    sig=sqrt(m2c-(npix/(npix-1.))*avc^2)         ;standard deviation, sum
    snr=sqrt(avc)                                ;signal-to-noise ratio
;
      print,'  average count of sum =',avc
      print,'  sigma =',sig,'  S/N =',snr
      print,'   '
    sum=rebin(imsum,404,404,/sample)
    ren=sum/m
    one=rebin(imn,404,404,/sample)
      print,'    sum = image rebinned to 404x404'
      print,'    ren = sum renormalized to average count'
      print,'    one = single rebinned image'
      print,'   '
 end
```

```
;Pro RD201.PRO
;analysis program for perfect images generated by POLMAP201 programs
;program is stored under the file name rd201


file=''
read,'    Name of image file:    ',file
get_lun,unit
openr,unit,file
pix=fltarr(5)
hdr=string('',format='(A41)')
readf,unit,pix,format='(4f8.5,e11.4)'
readf,unit,hdr

xc=pix(0)
yc=pix(1)
flux=pix(4)

   imm=fltarr(201,201)
   readf,unit,imm,format='(201e10.4)'
   imlog=alog10(imm>1.)
   psf=rebin(imm,402,402,/sample)
   pslog=rebin(imlog,402,402,/sample)

   print,'   '
   print,'pixel    ',pix
   print,'header   ',hdr

   print,'   '
   print,'          IMAGE is ready for display'
   print,'   '
   print,'    imm(imlog) = 201x201 linear(log) image'
   print,'    psf(pslog) = 402x402 linear(log) image'
   print,'   '

free_lun,unit
end
```

```
;Pro RDandBLUR.PRO
;read program for perfect images generated by POLMAP201 programs
;program is stored under the file name rdnblur


file=''
read,'    Name of image file:    ',file
get_lun,unit
openr,unit,file
pix=fltarr(5)
hdr=string('',format='(A41)')
readf,unit,pix,format='(4f8.5,e11.4)'
readf,unit,hdr

xc=pix(0)
yc=pix(1)
flux=pix(4)

   imm=fltarr(201,201)
   readf,unit,imm,format='(201e10.4)'

     ker=fltarr(3,3)
     ker(0,0)=0.014
     ker(0,1)=0.078
     ker(0,2)=0.014
     ker(1,0)=0.080
     ker(1,1)=0.635
     ker(1,2)=0.080
     ker(2,0)=0.016
     ker(2,1)=0.067
     ker(2,2)=0.016
     imcv=convol(imm,ker)
     imm=imcv
;
   imlog=alog10(imm>1.)
   psf=rebin(imm,402,402,/sample)
   pslog=rebin(imlog,402,402,/sample)

   print,'   '
   print,'pixel    ',pix
   print,'header   ',hdr

   print,'   '
   print,'          IMAGE is ready for display'
   print,'   '
   print,'    imm(imlog) = 201x201 linear(log) image'
   print,'    psf(pslog) = 402x402 linear(log) image'
   print,'   '

 free_lun,unit
 end
```

```
;pmod201.pro
;Pro program to generate noise for 201x201 model image
;imm = model image read with rd201
;

  imn=fltarr(201,201)
  imsum=fltarr(201,201)
  iplan=fltarr(201,201)
; values of xp,yp read separately
    print,'  Jupiter factor JF = 1 if SNR = 1 for'
    read,'   planet in single image - enter JF:  ',jf
    pcount=jf*sqrt(imm(xp,yp))
    iplan(xp,yp)=pcount
      print,'  enter 1 if planet PSF centered'
      read,'   on single pixel, else enter 0:   ',ncen
    if (ncen ne 1) then iplan(xp:xp+1,yp:yp+1)=pcount/4.
;
;noise arrays calculated
  starn=sqrt(imm)
  plann=sqrt(iplan)
;
read,'  number of images = ',m
  for i=0,m-1 do begin
    nfs=randomn(seed,201,201)
    snoise=starn*nfs
    nfp=randomn(seed,201,201)
    pnoise=plann*nfp
    imn=imm+snoise+iplan+pnoise
    imsum=imsum+imn
  endfor
;three images rebinned: model, single noisy, sum
    per=rebin(imm,402,402,/sample)
    one=rebin(imn,402,402,/sample)
    sum=rebin(imsum,402,402,/sample)
      print,'   '
      print,'  rebinned images (402x402) are per, one, sum'
end
```

```
;modadd.pro
;program to add shifted model images to reduce noise
;intent is to produce what might be called a "super-image"


;calculation of single noisy image
    nf=randomn(seed,201,201)
    noise=sqrt(imm)*nf
    imn=imm+noise

;shift and add noisy image
    ims=fltarr(197,197)
    ims=imn(1:197,1:197)+imn(2:198,1:197)+imn(3:199,1:197)+$
        imn(1:197,2:198)+imn(2:198,2:198)+imn(3:199,2:198)+$
        imn(1:197,3:199)+imn(2:198,3:199)+imn(3:199,3:199)
    ims=ims/9.

;rebin for display
    im1=rebin(imn(2:198,2:198),394,394,/sample)
    im9=rebin(ims,394,394,/sample)
    print,'   '
    print,'   im1 = single image rebinned to 394x394'
    print,'   im9 = shifted/summed image rebinned to 394x394'
end
```